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Subsonic Aircraft Safety Icing Study

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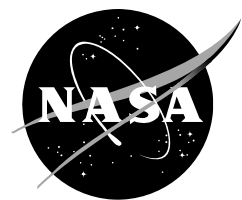
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EXECUTIVE SUMMARY

Of the four types of operations (i.e., Federal Aviation Regulation (FAR) Part 121, Part Scheduled 135, Nonscheduled Part 135 and Part 91) that were examined, Scheduled Part 135 shows the highest percentage of total accidents that involve icing (8.0 percent), the highest percentage of fatal accidents that involve icing (8.2 percent) and the highest percentage of fatalities in icing-related accidents (16.2% percent).

If ramp- and security-related accidents are eliminated from the dataset, 9.5 percent of the total fatal air-carrier (Part 121) accidents are due to icing. This percentage is greater than for general aviation (Part 91) and commuter/air taxi (Part 135), which are 3.7 percent and 8 percent respectively. However, no fatal Part 121 icing-related accidents have occurred since 1994.

Of the six Part 121 icing-related accidents in the dataset, three had turboprop engines, and the others were equipped with turbofan or turbojet engines.

The highest percentage of icing-related reports in the voluntary Aviation Safety Reporting System (ASRS) database occurred in 2005, but the overall number of these events relative to the total is small (less than 1 percent). Of the 663 icing incidents reported, 141 resulted in the crew declaring an emergency.

In Petty and Floyd's review of airframe icing accidents from 1982-2000, 60 percent of Part 121 accidents were fatal compared with 47 percent of general aviation (Part 91) accidents and 26 percent of Part 135 accidents during the same time period.

Only 0.5 percent of U.S. Army aircraft accidents are icing related, but this number is still of concern due to the Army's strict regulations that forbid flight into known or severe icing conditions.

A review of several studies by subject-matter experts was summarized into four high-priority icing research areas: (1) improved propulsion system tolerance to weather, (2) development of methods to sense and document actual icing conditions, (3) research to identify realistic ice accumulations to improve aircraft certification and pilot training, and (4) aircraft performance and handling qualities in icing conditions.

Based on the Integrated Resilient Aircraft Control (IRAC) Project goals and objectives, the IRAC project is encouraged to conduct work in all of the high-priority icing research areas that were identified, with the exception of the developing of methods to sense and document actual icing conditions.

1. INTRODUCTION

1.1 Purpose of Study

NASA's Integrated Resilient Aircraft Control (IRAC) Project is one of four projects within the agency's Aviation Safety Program (AvSafe) in the Aeronautics Research Mission Directorate (ARMD). The IRAC Project, which was redesigned in the first half of 2007, conducts research to advance the state of the art in aircraft control design tools and techniques. The purpose of this research is to ensure flight safety by providing on-board aircraft control resiliency even in the presence of adverse events, including loss of control caused by environmental factors (e.g., wind, icing), and actuator and sensor faults or failures (ref. 1 and 2). The significance of icing in the safety of subsonic transports is inconclusive based on the following statements:

"Note that Icing Challenge is primarily a general aviation problem. Not seen by community as an issue in large transport category aircraft" (ref. 1).

"Historical data also indicates icing is primarily considered a general aviation and Part 135 issue" (ref. 1).

"General aviation and Part 135 aircraft traditionally fly at lower altitudes and at slower speeds than air transport category aircraft; as a result, they are more likely to encounter icing conditions, including SLD (supercooled liquid droplets) environments" (ref. 3).

As a result, a "Key Decision Point" (ref. 1) was established for fiscal year 2007 with the following expected outcomes (ref. 1):

- (1) "Report and document utilizing the most current statistical/prognostic data available from National Transportation Safety Board (NTSB) and Aviation Safety Information Analysis and Sharing (ASIAS), the reports, incidents and accidents associated with icing for subsonic transports.
- (2) Report by subject matter experts in icing research on current knowledge of icing effects on control parameters.
- (3) Establish future requirements for icing research for subsonic transports including the appropriate alignment (IVHM: identification, IIFD: sensing and IRAC: flight control)"

1.2 Overview of Study Contents

The expected outcomes for this study are addressed in sequential order. Outcome 1 is addressed in section 2, which contains statistical analyses of accident and incident data; these analyses have been conducted by NASA researchers for this "Key Decision Point." Outcome 1 is also addressed in section 3, which contains an examination of icing in other recent statistically based studies. Outcome 2 is the focus of section 4, which is a summary of aviation safety priority lists that have been developed by various subject-matter experts, including the significance of aircraft icing research in these lists. Suggested future requirements for NASA icing research (outcome 3) are presented in section 5. Finally, discussion and the conclusions that have been drawn are provided in section 6.

2. NASA STATISTICAL ANALYSES

As stated previously, the first expected outcome of this study is a report that documents the results of an examination of the most recent statistical/prognostic incident and accident data that is available to determine the significance of icing in subsonic transport accidents and incidents. This section contains the results of two separate statistical analyses that have been conducted by NASA to address this expected outcome. In the first statistical analysis, publicly available NTSB and Federal Aviation Administration (FAA) accident and incident data were examined. A second statistical analysis was also conducted using the Aviation Safety Reporting System (ASRS) reports as the data source.

2.1 NASA Analysis of NTSB Accident and Incident (A/I) Data

A statistical analysis was conducted to look at trends in the number of icing-related events across a 16 year span (1988-2003) within the four areas of flight operation (Part 121, Scheduled Part 135, Nonscheduled Part 135, and Part 91). The word “event” is used here to encompass both accidents and incidents. These types of operations are also known as general aviation (Part 91), commuter/air taxi (Part 135), and air carrier (Part 121). In March 1997, the FAA changed the rules for the classification of major airlines so that air carriers with 10 or more seats, which previously were handled under Part 135 operations, would now be handled under Part 121 operations (ref. 4). The source for accident data is the NTSB Aviation Accident and Incident Data System, while the source for incident data is the FAA’s Accident/Incident Data System. Although both databases contain accident and incident data, the FAA has primary investigative responsibility for incidents, and the NTSB is the authority for accident investigation.

Icing events were selected from the accident data in two ways. First, those accidents that had previously (ref. 5) been assigned the “Ice” category (using the Commercial Aviation Safety Team/International Civil Aviation Organization (CAST/ICAO) Common Taxonomy Team (ref. 6) accident category taxonomy) were separated from the rest of the accidents. These events included both on-ground and in-flight aircraft icing but did not include runway-surface icing. Some engine icing was included in this group, but only if airframe icing conditions also existed (i.e, rather than just carburetor icing). Also included were events that involved Pitot system icing, windshield icing, or in-flight icing of slush packed in the wheel wells. Second, accidents were selected that included a loss of engine power as a result of carburetor or induction icing, but for which no airframe icing was indicated; this is almost exclusively a general aviation phenomenon.

Selection of icing events from the incident data was accomplished based on the following criteria: (1) if the data record indicated icing as a primary or secondary cause, or (2) if the words “ice,” “icing,” or “freezing rain” were found in the narrative text. All of these records were reviewed; those that involved only ground surface (runway) icing were excluded as were those in which the narrative specified an absence of icing conditions. Events that included a loss of engine power as a result of carburetor icing, induction icing or ice ingestion were not excluded.

A summary of the number of icing events can be found in Table 1. Data for total flight hours per year were obtained from the tables that are published by the NTSB (ref. 7), which are based on data that is supplied by the FAA. Icing contributes to a very small percentage of accidents and incidents, that is, only 3.5 percent of accidents overall and 1.3 percent of incidents. However, fatal icing accidents comprise 4 percent of all fatal accidents, and 4.5 percent of all fatalities occurred in icing-related accidents (aggregate data not shown). Part 135 has the highest

percentage of icing-related events (as compared with the total number of accidents, both total and fatal) and the largest flight-hour-adjusted rates. By far the largest percentage of icing fatalities (as compared with total fatalities) is within Scheduled Part 135 operations (16.2 percent), and the percentages in other flight categories are remarkably similar to one another (between 4.0 percent and 4.6 percent). Among fatal accidents, the lowest percentage that is attributable to icing is for Part 91 (3.6 percent), which is less than half the rate for Nonscheduled Part 135 operations (7.9 percent).

Table 1. Types of Icing Events by Flight Operation

Type of event	Operation			
	Part 121	Scheduled Part 135	Nonscheduled Part 135	Part 91
Total flight hours	232,868,640	25,050,928	46,350,000	416,319,000
Total fatal accidents	60	49	278	4599
Fatal accidents with icing conditions	4 (6.7%)	4 (8.2%)	22 (7.9%)	165 (3.6%)
Total fatalities	2151	328	664	8724
Fatalities with icing conditions	99 (4.6%)	53 (16.2%)	27 (4.1%)	350 (4.0%)
Total accidents	600	213	1070	23349
Accidents with icing conditions	6 (1.0%)	17 (8.0%)	58 (5.4%)	321 (1.4%)
Icing accidents per million flight hours	0.0258	0.679	1.25	0.771
Accidents with carburetor icing only			3 (0.3%)	467 (2.0%)
Carburetor icing accidents per million flight hours			0.065	1.122
Total incidents	7497	2218	2082	29167
Incidents with icing or carburetor icing conditions	50 (0.7%)	32 (1.4%)	48 (2.3%)	390 (1.3%)
Icing or carburetor icing incidents per million flight hours	0.215	1.277	1.036	0.937

Green suggests in his report on icing (ref. 8), that a relationship may exist between icing events and aircraft size. Many of the same aircraft are flown under Part 91 and Part 135, so one might expect the icing rates to be more similar in those groups. Perhaps the pilots who are operating under Part 91 are more able to delay their flights to avoid icing conditions, or perhaps the pilots who are operating under Part 135 overestimate either their own ability or the aircraft's ability to handle the icing conditions.

In prior NASA examinations of aircraft accident rates (ref. 9), ramp-related events were not included because these events were perceived as occupational-health-related events. Security-related events were also excluded because they fall under the domain of the Department of Homeland Security. Therefore, we decided to look within this same data subset at the significance of icing events. Specifically, we eliminated all security-related events (109 total events) and those for which the predominant issue was a ground-handling or ramp error (e.g. ground-crew errors, pushback/tow issues, inadequate preflight inspection). Ninety-five percent of these ground-handling accidents (274 total events) took place while the aircraft was on the ground or during takeoff; the remainder involved mostly separated doors or engine cowlings.

Part 121 is the only operation that is impacted by this change (see Table 2). The percentage of fatal accidents that are attributable to icing jumps from 6.7 percent to 9.5 percent (now the highest of the four percentages), and the percentage of total fatalities jumps from 4.6 percent to 6.2 percent (now second highest among the four groups).

**Table 2. Types of Icing Events by Flight Operation
(Without ramp and security events)**

Type of event	Operation			
	Part 121	Schedule Part 135	Nonscheduled Part 135	Part 91
Total flight hours	232,868,640	25,050,928	46,350,000	416,319,000
Total fatal accidents	42	48	275	4511
Fatal accidents with icing conditions	4 (9.5%)	4 (8.3%)	22 (8.0%)	165 (3.7%)
Total fatalities	1603	327	660	8628
Fatalities with icing conditions	99 (6.2%)	53 (16.2%)	27 (4.1%)	350 (4.1%)
Total accidents	534	203	1057	23055
Accidents with icing conditions	6 (1.1%)	17 (8.4%)	58 (5.5%)	321 (1.4%)

The icing-related events, shown as a percentage of total fatal accidents, total fatalities, and total accidents in Tables 1 and 2 are displayed in a side-by-side graphical format in the next three figures. For each of the four operations, icing-related accidents and incidents are displayed both with and without ramp- and security-related events. Again, note that the most visually significant difference occurs in the percentage of fatal accidents with icing conditions for Part 121 operations (see Figure 1).

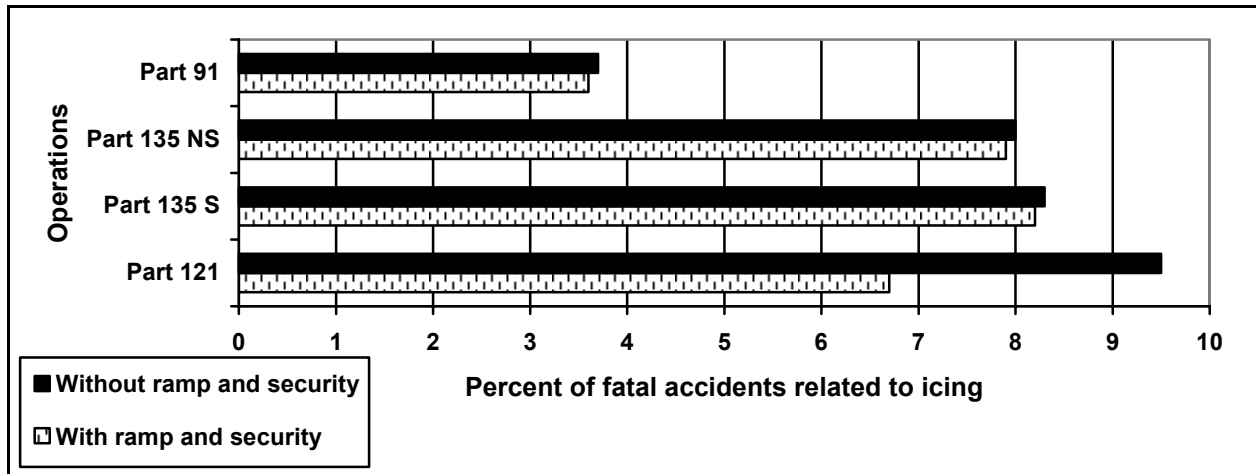


Figure 1. Fatal accidents with icing conditions.

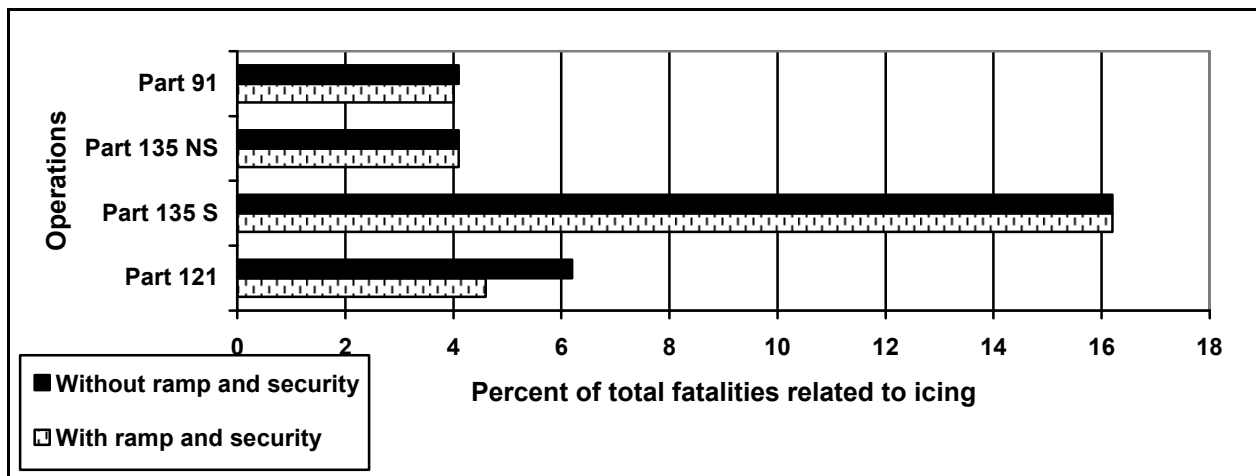


Figure 2. Total fatalities with icing conditions.

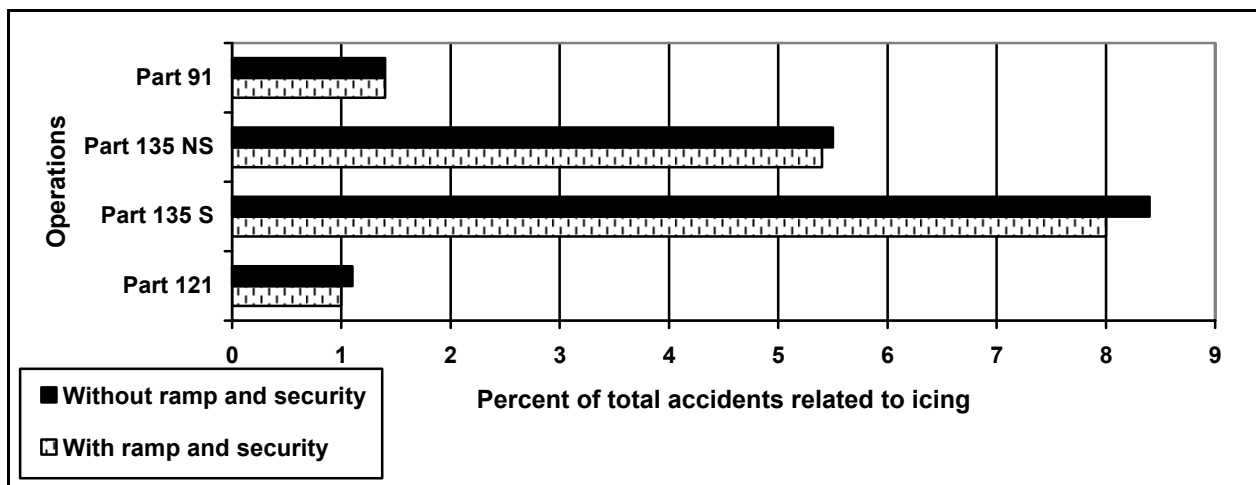


Figure 3. Total accidents with icing conditions.

Since 1988, no more than five icing-related events have occurred per year during Part 121 flights, and the overwhelming majority of those were incidents (see Figure 4). In 35 of the 56 events, no damage to the aircraft was noted and no injuries occurred. However, in four of the six accidents, the aircraft was destroyed, and fatal injuries occurred. A total of 99 persons died in icing-related accidents, but no fatal icing-related accidents have occurred since 1994. A downward trend is evident in the flight-hour-adjusted rates for icing events (see Figure 5).

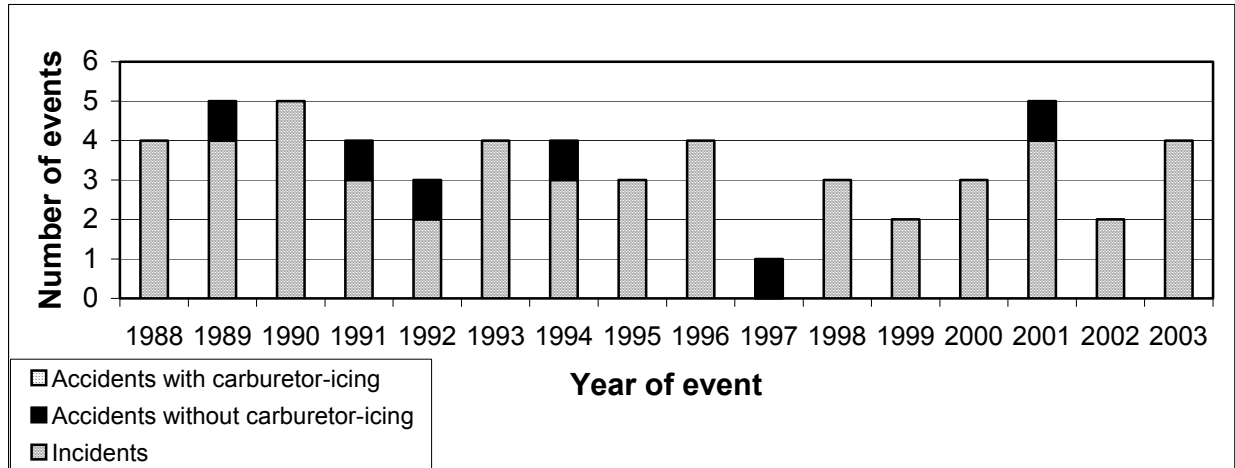


Figure 4. Number of Part 121 icing events per year.

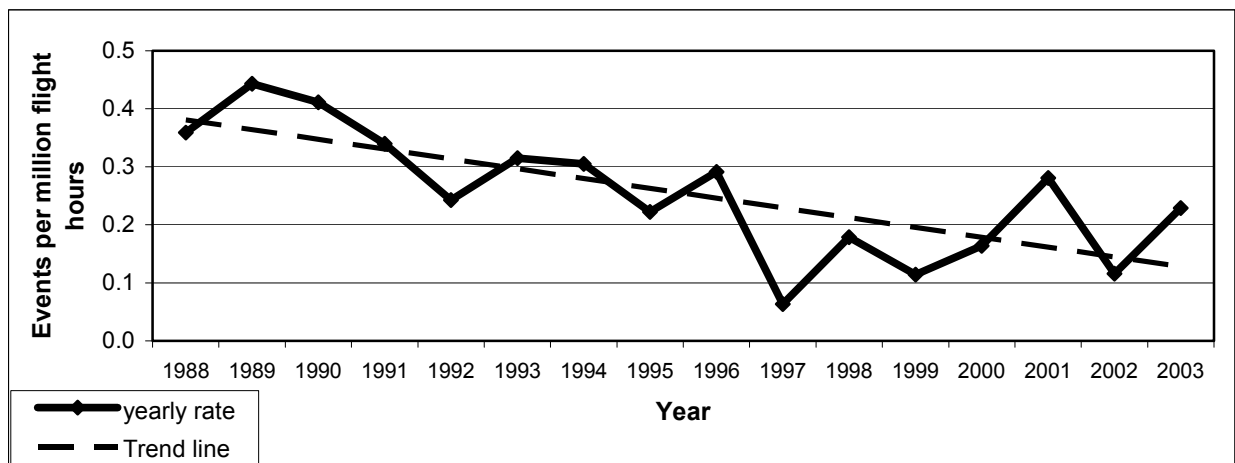


Figure 5. Rate of Part 121 icing events (per million flight hours).

Among Scheduled Part 135 operations, more than 70 percent (35 of 49) of the icing events that are included in this analysis (see Figure 6) occurred prior to 1995, but just over half of the icing accidents (9 out of 17) have occurred since 1994. The flight-hour-adjusted rates for icing events may be increasing slightly (see Figure 7), or this may be an artifact of the major decrease in flight hours that is noted for Scheduled Part 135 operations since 1997. Of the four types of flight operations that were examined, Scheduled Part 135 operations show the highest

percentage of total accidents that involve icing (8.0 percent), the highest percentage of fatal accidents that involve icing (8.2 percent), and the highest percentage of fatalities in icing accidents (16.2 percent).

Only one of the four fatal accidents occurred prior to 1990; one-third of the accidents since 1994 (3 of 9) included a fatality. Five of the nine most recent accidents (two of which were fatal) had inadequate ice removal prior to takeoff, which led to an overrun of the runway on an aborted takeoff in one event and a loss of control during the takeoff climb in the remaining four accidents. No injuries occurred in 9 of the 17 accidents, and no damage to the aircraft occurred in 28 of the 32 incidents.

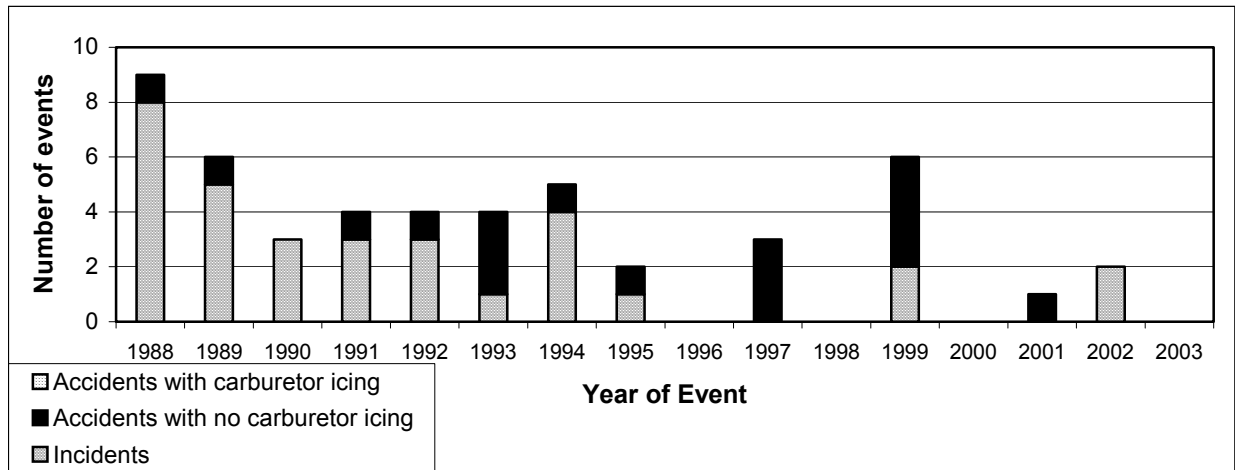


Figure 6. Number of Scheduled Part 135 icing events per year.

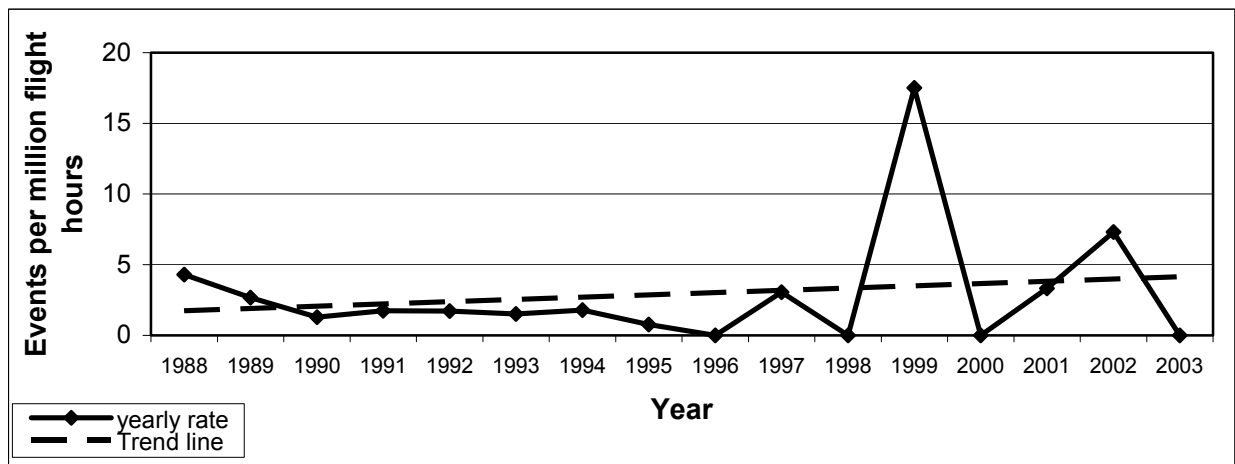


Figure 7. Rate of Scheduled Part 135 icing events (per million flight hours).

Among Nonscheduled Part 135 flights, slightly more icing-related accidents than incidents occurred in most years (see Figure 8). Of the four flight groups examined, Nonscheduled Part

135-NS had the highest percentage of icing-related incidents (2.3 percent) and the second highest percentage of both icing-related accidents (5.7 percent) and icing-related fatal accidents (7.9 percent). Only 27 persons died in Nonscheduled Part 135 icing-related accidents. No injuries occurred in 21 of the 61 accidents, and no damage to the aircraft occurred in 22 of the 48 incidents. A slight downward trend is evident in the flight-hour-adjusted rates for icing-related Nonscheduled Part 135 events (see Figure 9).

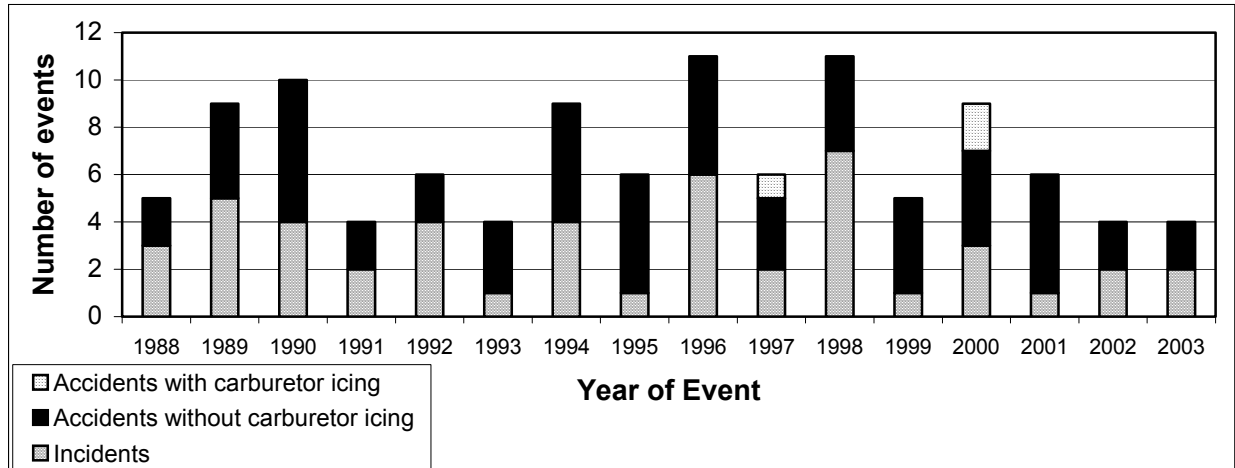


Figure 8. Number of Nonscheduled Part 135 icing events per year.

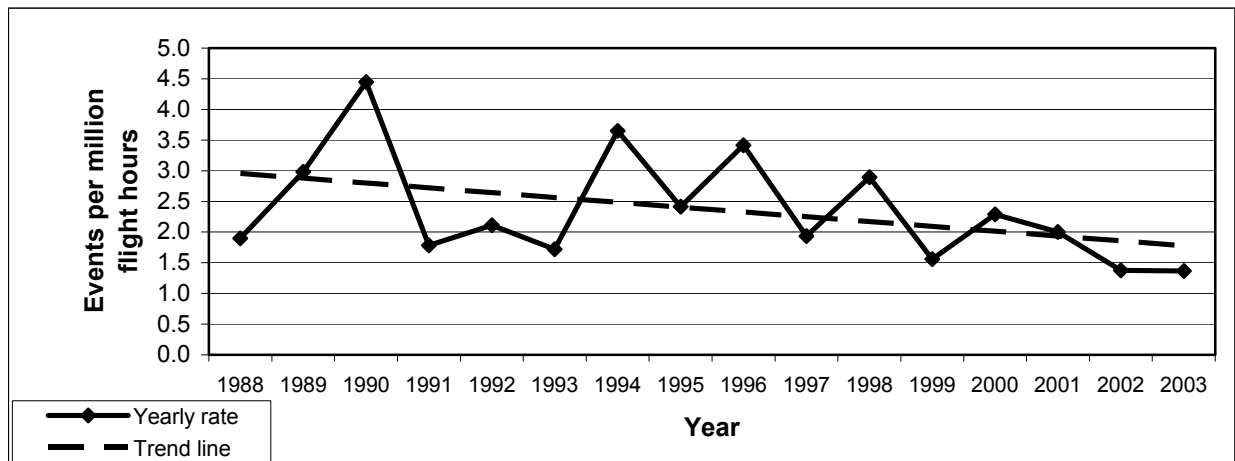


Figure 9. Rate of Nonscheduled Part 135 icing events (per million flight hours).

In the eight years prior to and including 1995, the average number of Part 91 icing-related events was 98. In the next eight years (1996-2003), the average dropped to 49 (see Figure 10). The largest drop was among incidents (from 36 to 12), and the smallest drop was among the icing accidents that did not involve carburetor icing (from 24 to 16). A significant decrease was noted in the flight-hour-adjusted rates for icing-related events (see Figure 11). Only 3.6 percent of fatal Part 91 accidents were related to icing; this was the lowest percentage among the four

flight categories that were examined. Although 350 persons died in icing-related accidents, this represents only 4 percent of all Part 91 deaths in this time period (again, the lowest of the four percentages). No injuries occurred in nearly half of the icing-related accidents (390 of 788), and no aircraft damage occurred in 229 of the 390 incidents (59 percent).

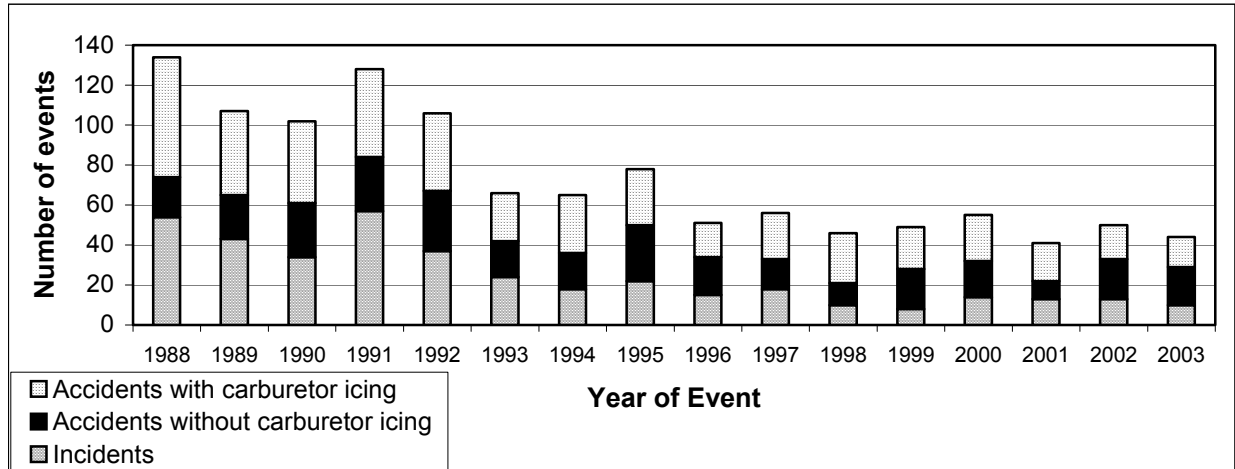


Figure 10. Number of Part 91 icing events per year.

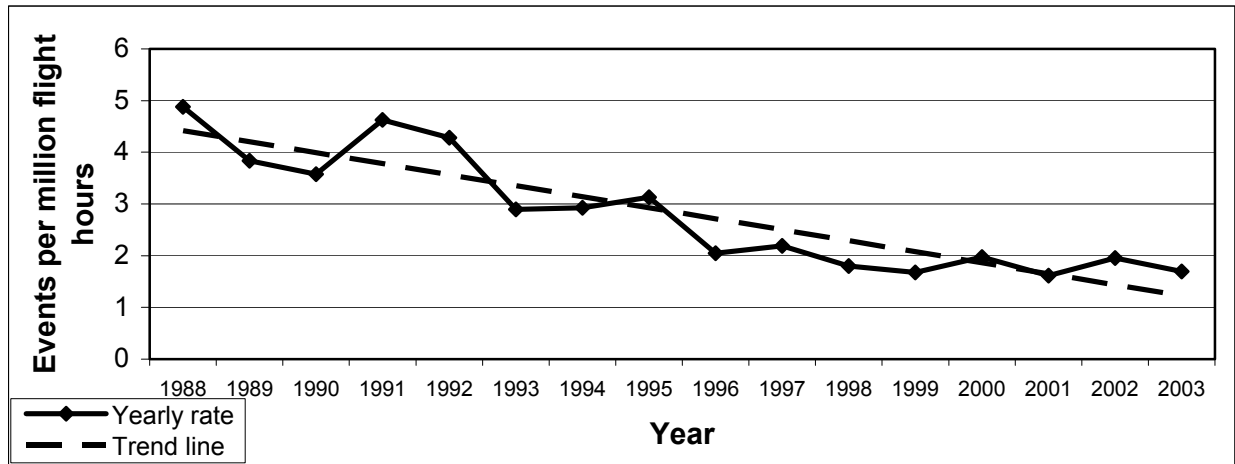


Figure 11. Rate of Part 91 icing events (per million flight hours).

Each accident report specifies the type of engine that was installed on the aircraft. Because the IRAC project includes engine research, an examination was conducted of all events in the dataset based on engine type. The possible engine types (ref. 10-14) are:

- Reciprocating: Also known as a piston engine, the reciprocating engine is a heat engine that uses one or more pistons to convert pressure into a rotating motion.
- Turbojet: Turbojet engines are inefficient and noisy engines that are used by mostly older aircraft and consist of an air inlet, air compressor, combustion chamber, gas

turbine, and nozzle. These engines are the simplest and oldest kind of general-purpose jet engine.

- **Turboprop:** Turboprop engines are similar to turbojet engines except that additional stages are included in the turbine to recover more power to turn the propeller. Turboprop engines are generally used on small or slow subsonic aircraft because they are highly efficient at modest flight speeds (i.e., below 450 mph).
- **Turbofan:** A turbofan engine is similar to a turbojet engine and essentially consists of a ducted fan with a smaller diameter turbojet engine that is mounted behind it to power the fan. Turbofans are used by most large commercial aircraft because of their fuel efficiency and quiet operation.
- **Turboshaft:** In principle, a turboshaft engine is similar to a turbojet engine, except that it features additional turbine expansion to extract heat energy from the exhaust and convert it to output shaft power. The name turboshaft is most commonly applied to engines that power ships, helicopters, tanks, locomotives, and hovercraft.

For a small number of accidents, the engine type is unknown. Figures 12 through 15 display the percentage of total accidents each year for which the aircraft engine was of a particular type.

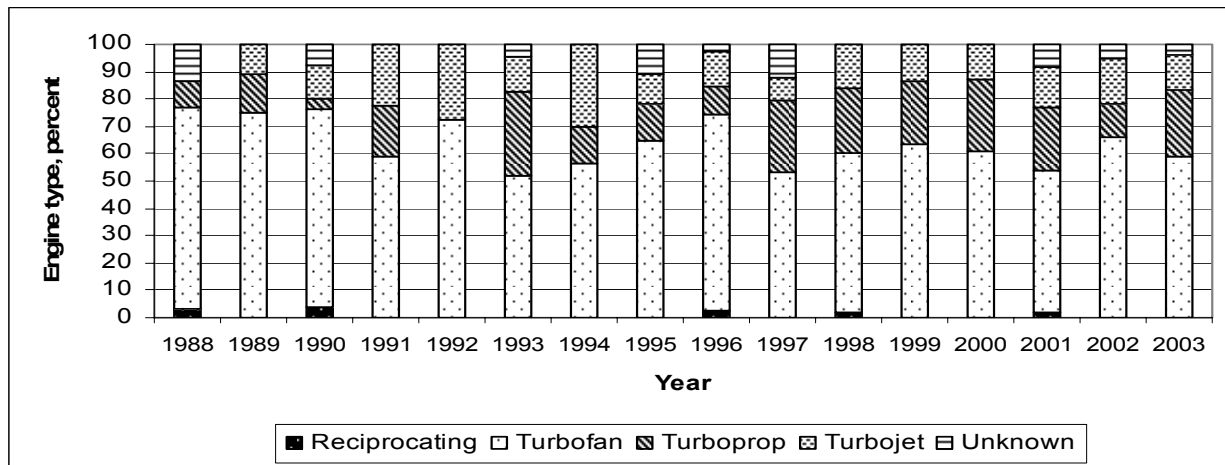


Figure 12. Part 121 accidents by engine type.

Part 121 aircraft (see Figure 12) use primarily turbofan engines (62 percent overall), although the number of turboprops engines (19 percent overall) increased in 1997 (when Part 121 was expanded to include flights that previously would have been considered Part 135).

Scheduled Part 135 aircraft (see Figure 13) use either reciprocating engines (52 percent) or turboprop engines (44 percent) almost exclusively.

Nonscheduled Part 135 aircraft (see Figure 14) primarily have used reciprocating engines (79 percent), with turboprop engines (15 percent) becoming more popular in recent years. Part 91 aircraft (see Figure 15) use reciprocating engines almost exclusively (96 percent overall).

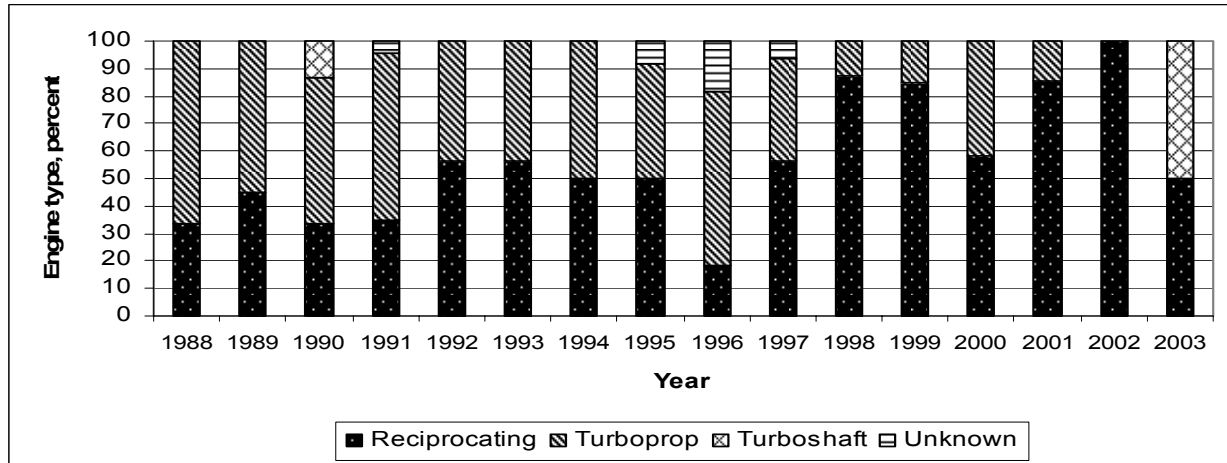


Figure 13. Scheduled Part 135 accidents by engine type.

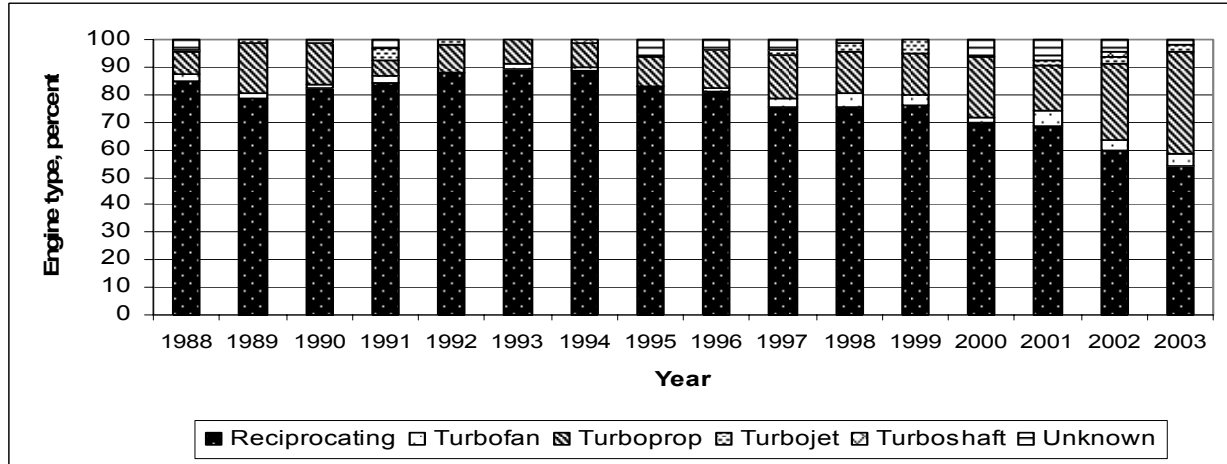


Figure 14. Nonscheduled Part 135 accidents by engine type.

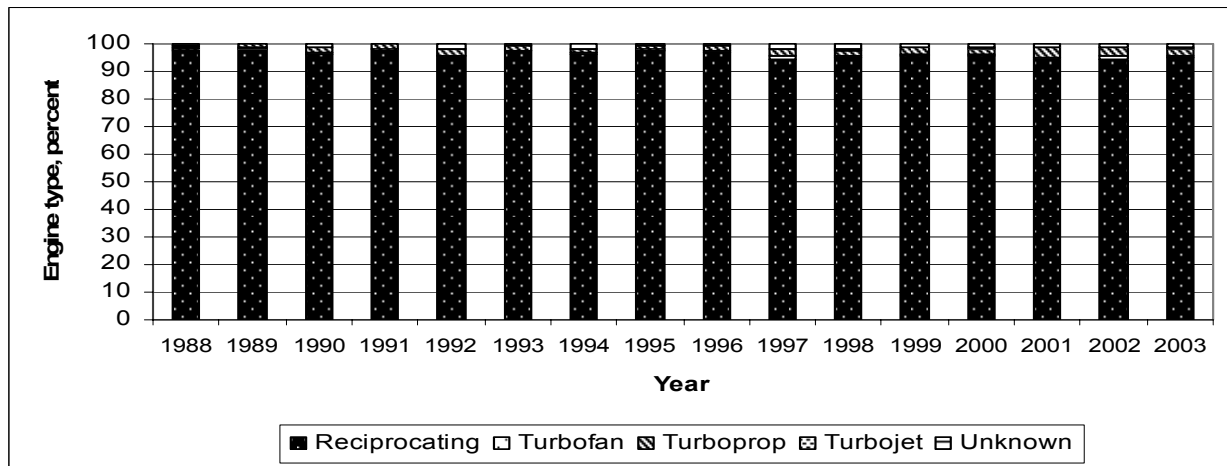


Figure 15 - Part 91 accidents by engine type.

Figures 16 through 19 present the same information as shown in Figures 12-15, for only those accidents that involved fatalities.

For Part 121 operations (see Figure 16), more than half (55 percent) of the fatal accidents occurred in aircraft with turbofan engines, but this is still less than the percentage (62 percent) of aircraft with turbofan engines that were involved in both fatal and nonfatal accidents. The percentage of turboprop engines was also slightly lower (13 percent rather than 19 percent), while relatively more fatal accidents occurred with reciprocating, turbojet, and unknown engine types. In particular, 13 percent of the fatal accidents have unknown engine types. In 2002, no Part 121 accidents included a fatality.

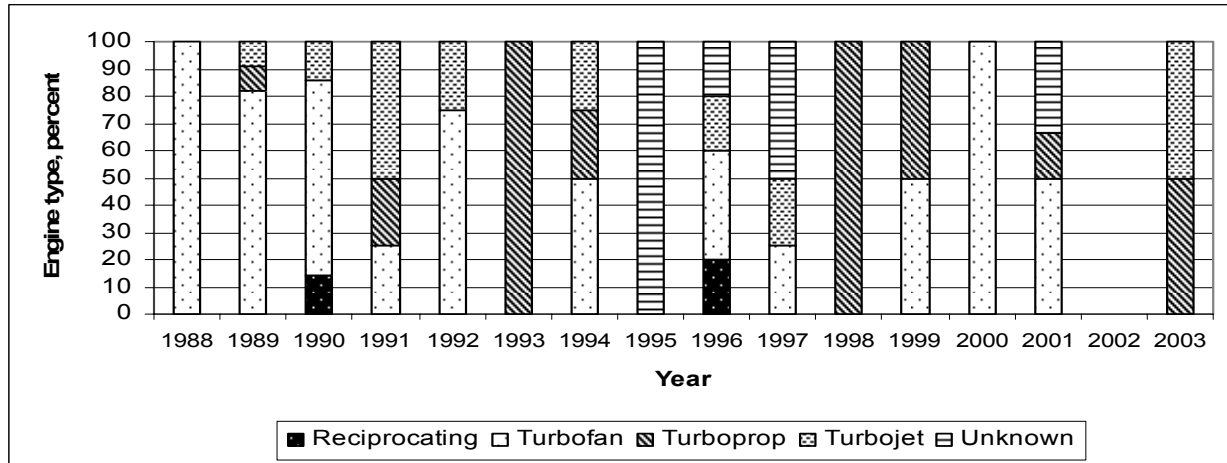


Figure 16. Part 121 fatal accidents by engine type.

For Scheduled Part 135 operations (see Figure 17), the percentages for fatal accidents are similar to those for all accidents with respect to engine type. The fatal accidents occurred predominantly on aircraft with reciprocating or turboprop engines (96 percent), with slightly more fatal accidents on aircraft with turboprop engines (51 percent). No fatal accidents occurred in 1998 and 2002.

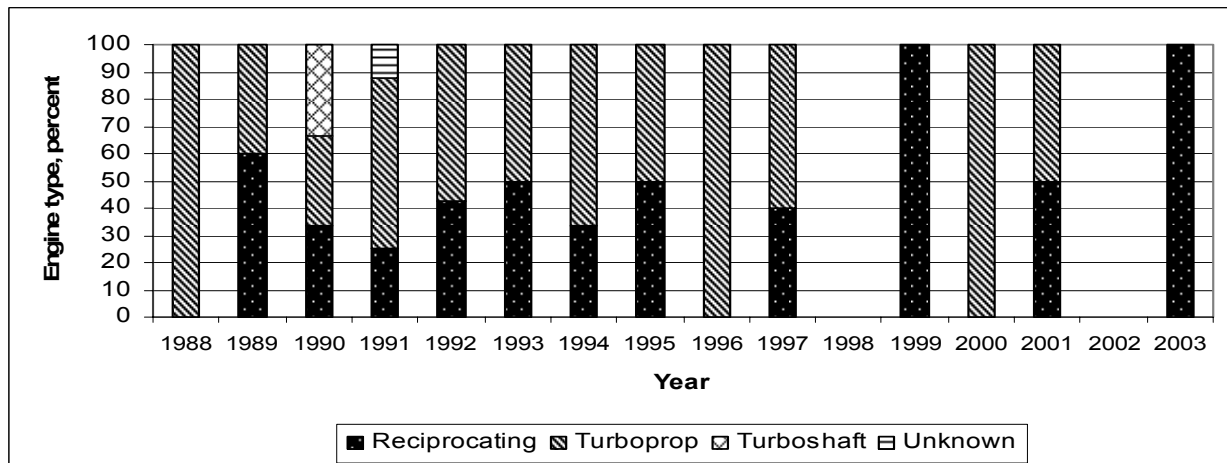


Figure 17. Scheduled Part 135 fatal accidents by engine type.

For both Nonscheduled Part 135 (see Figure 18) and Part 91 operations (see Figure 19), the distribution of engine type in fatal accidents is remarkably similar to that for fatal/non-fatal accidents combined. The percentages for fatal accidents in turboprop aircraft were slightly higher than for the combined group (16.5 percent versus 15 percent for Nonscheduled Part 135; 4 percent versus 2 percent for Part 91 respectively).

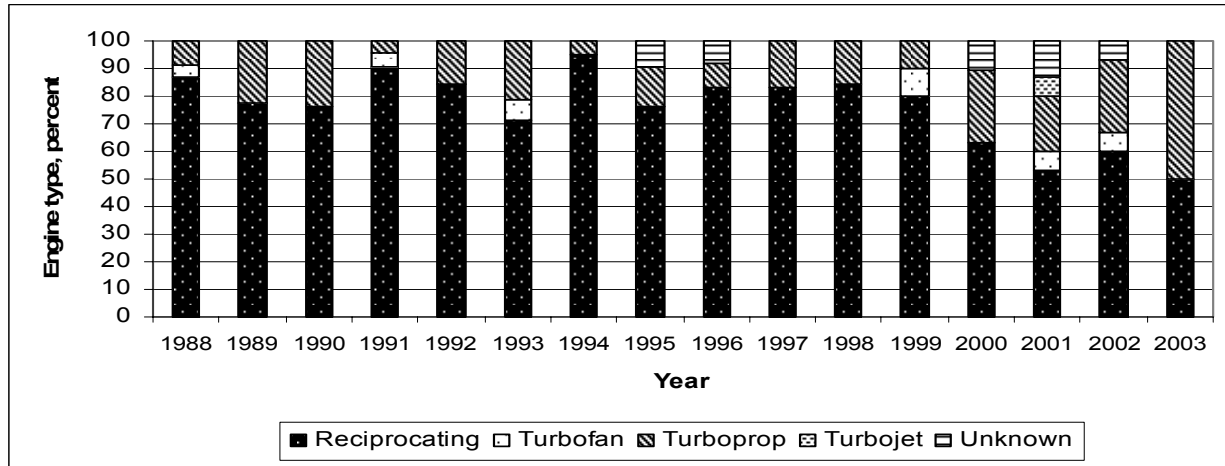


Figure 18. Nonscheduled Part 135 fatal accidents by engine type.

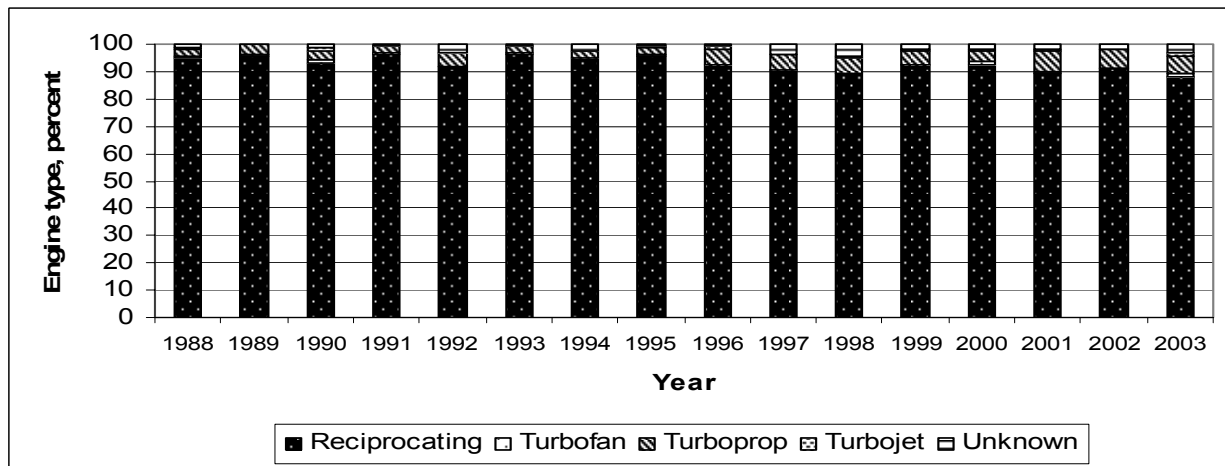


Figure 19. Part 91 fatal accidents by engine type.

Recall that when ramp- and security-related accidents were eliminated from the dataset (see Table 2), 9.5 percent of the total fatal air carrier (Part 121) accidents were caused by icing. This percentage is greater than that for general aviation (Part 91) or commuter/air taxi (Part 135), which were 3.7 percent and 8 percent respectively. The aviation community generally attributes the large number of icing accidents in Part 121 operations to aircraft with turboprop engines and because a reduction in the use of turboprop engines has been noted for Part 121 operations during the past 10 years, aviation experts assume that icing is no longer a significant problem for Part 121 operations. This assumption is disputed for two reasons. First, although the majority of Part 121 operators indeed use jet aircraft, turboprop and piston engines still

comprise a significant portion of the this operating category. For example, in 2004, 59 percent of the passenger aircraft used by regional airlines had jet engines, but turboprop and piston (i.e. reciprocating) engines accounted for an additional 41 percent of the aircraft in operation (ref. 15). Second, although two of the four fatal Part 121 icing accidents that occurred during the period of study were in turboprops, the other fatal accidents involved aircraft that were equipped with turbofan and turbojet engines (see Table 3).

Table 3. Part 121 Fatal Icing Accidents

Event date	Location	Airline	Engine type
3/15/89	West Lafayette, IN	Mid Pacific	Turboprop
2/17/91	Cleveland, OH	Ryan International	Turbojet
3/22/92	Flushing, NY	US Air	Turbofan
10/31/94	Roselawn, IN	American Eagle	Turboprop

2.2 NASA Analysis of ASRS Data

Database

The data in this section of the report were gathered from the ASRS database. As of the writing of this report, the database archives incident reports that were submitted between January 1988 and February 2007. The total number of reports in the database from this time period is a little less than 137,000.

The ASRS is a voluntary reporting system, and reports can be submitted by anyone who is involved in an incident. The majority of the reports appear to be filed by the flight crew. All of the reports that are accepted into the ASRS database have been reviewed, screened, and coded by an analyst. The proportion of reported incidents that are rejected is unknown.

The ASRS database is accessible online at <http://asrs.arc.nasa.gov>.

Methodology

The data set used in this analysis consists of 663 reports that are highly likely to have icing as a significant factor. To retrieve these reports, we used the ASRS online search tool. The query had two parts:

- 1) Primary problem: weather
- 2) Free text search string:
"ic% OR rime OR rhime OR de-ice OR deice OR sleet OR frost"

The *Primary problem* field has 16 possible category selections which are mutually exclusive. The free text search is performed across three fields: narrative, synopsis, and keywords. The narrative is a part of the raw report, and is retained just as it was submitted by the reporter. The synopsis and keywords are added by an analyst later.

While developing the search string, we checked possible alternate spellings of *sleet*—"slete," "sleat," and "sle%" - and found no occurrences of these alternate spellings. In his report, Green's (ref. 8) search string included the term *glaze*. We did not include this term because each report that contained the word *glaze* in reference to an environmental factor also contained the word *ice*. (Five such reports met this criterion.) In the single report in which the word *glaze* appeared without the term *ice*, it referred to the condition of someone's eyes.

Although most or all of the reports in the data set appear to involve engine or wing icing, the reports have not been reviewed exhaustively. From our experience with the database, we know that weather-related ice problems also can refer to ice on the runway as well as the aircraft.

Icing-Related Incidents Versus All Weather-Related Incidents

We compared the number of icing-related incidents with both the total number of incidents and the total number of weather-related incidents that were reported over the last 10 years (see Table 4). We use the term *weather incidents* to mean the incidents that are retrieved by searching for items that have weather as the primary cause.

In all years, the number of icing-related incidents is very small relative to the total number of incidents. However, icing is a significant fraction of all weather-related incidents. Although the last three years show fewer weather incidents, note that fewer incidents overall were recorded for the same time period.

Table 4. Icing Versus Weather Incidents in ASRS

Year	Number of icing-related incidents	Percentage of incidents related to icing	Total Number of incidents	Percentage of incidents related to weather	Number of weather-related incidents
1997	52	0.65	8018	16	332
1998	34	0.40	8428	12	276
1999	29	0.29	9866	12	245
2000	38	0.48	7998	16	232
2001	21	0.24	8612	11	197
2002	26	0.36	7198	13	201
2003	32	0.39	8143	12	266
2004	27	0.44	6200	17	161
2005	25	0.71	3524	23	109
2006	11	0.21	5196	9	188

Incidents by FAR Operation

Incident reporters are responsible for documenting the FAR under which they were operating at the time of the incident. The applicable regulations for this field in the ASRS database are Parts 91, 119, 121, 125, 129, and 135; an *other* choice is provided for all others. In the icing data set, none of the aircraft were reported as operating under FAR Part 125.

Table 5 shows the number of icing-related incidents for selected FAR operations. The total number of incidents and the total number of weather-related incidents are included in this table for comparison purposes.

Table 5. Subset of ASRS Weather-Related Incidents by Select FAR Operation

Year	Part 91	Part 119	Part 121	Part 135	Number of weather-related incidents	Number of total incidents
1997	15	0	29	7	332	8018
1998	15	0	13	4	276	8428
1999	15	1	9	2	245	9866
2000	12	0	24	2	232	7998
2001	10	0	6	2	197	8612
2002	8	0	15	3	201	7198
2003	20	0	12	0	266	8143
2004	14	0	12	1	161	6200
2005	13	0	8	3	109	3524
2006	7	0	3	1	188	5196

Incidents by Flight Phase

For the *Flight phase* field, incident reporters can select multiple flight phases. A visual scan of the reports shows that nearly all of the reports specify multiple flight phases. This field allows primary categories and subcategories. Counts for the primary categories are given in Table 6.

Table 6. ASRS Icing-Related Incidents by Flight Phase

Flight Phase	Number of Incidents
Climb-out	98
Cruise	325
Descent	193
Ground	106
Landing	133

Incidents by Resolatory Actions

Resolatory actions are the actions taken by the flight crew or controller or other circumstances that occurred to resolve an anomaly during the flight. Of the 663 icing-related incidents, 141 resulted in the crew declaring an emergency, and 16 resulted in an emergency landing. In this analysis, we provide counts of the categories for those actions that included crew action but not for other types of actions (Table 7). These actions are not mutually exclusive; incident reporters could select more than one entry for this field.

Table 7. ASRS Icing-Related Incidents with Resolatory Actions

Resolatory Action	Number of Icing-Related Incidents
Declared emergency	141
Landed in emergency	16
Landed as precaution	7
Rejected takeoff	9
Executed go around	2

Incidents That Involved Carburetor Icing

Carburetor icing incidents were found by searching for the string “carb” within the narrative section of the report (Table 8). Of the 663 icing reports, this search returned 9 incidents that mentioned carburetor icing.

Table 8. ASRS Incidents With Carburetor Icing

Year	Count
1990	1
1994	1
1996	1
1998	2
2000	1
2001	1
2003	2

Incidents by Anomaly Classification

Incident reporters can select multiple entries for the *Anomaly* field. Of the 663 icing-related incidents, 172 reports contained *Aircraft equipment problem* as one of the anomalies. This anomaly can be further subcategorized into “critical” or “less severe”; 121 incidents were classified as critical, and 51 incidents were classified as less severe.

Although the anomalies can be subcategorized, only the primary anomalies are listed shown Table 9.

Table 9. ASRS Icing-Related Incidents by Anomaly Field

Anomaly	Number of icing-related incidents
Equipment problem	172
Airspace violation	5
Altitude deviation	165
Cabin event	8
Conflict (airborne or ground)	28
Excursions	156
Ground encounters	12
Incursion	7
In-flight encounter	532
Nonadherence	267
Other	415

Incidents by Engine Type

Table 10 shows the 663 incidents broken down by engine type.

Table 10: ASRS Icing-Related Incidents by Engine Type

Engine Type	Number of icing-related incidents
reciprocating	223
turbojet	208
turboprop	87
unknown	46

3. REVIEW OF PRIOR AVIATION STATISTICAL STUDIES

A number of previous studies have been conducted that examine historical aviation data to determine the impact of icing on accidents and incidents. One such study was funded by NASA (ref. 8). Two others were led by other agencies, such as the FAA; however NASA employees were members of the analysis teams. The remaining study was conducted by the NTSB without any known NASA interaction. Although many of the studies used the same databases for their analyses, considerable differences exist in their results due to the variations in the respective study assumptions and constraints.

3.1 Green Study of Inflight Icing

At the 2007 American Institute of Aeronautics and Astronautics conference in Reno, NV, Steven Green presented the results of his study of inflight icing accidents and incidents in the United States (ref. 8). Three databases were used for the study: (1) the NTSB Accident Database and Synopses, (2) the FAA Accident/Incident Data System (AIDS), and (3) the NASA Aviation Safety Reporting System (ASRS). Green searched for the terms “icing,” “freezing,” “rime,” “glaze,” “sleet” and “frost” in all three databases and narrowed the set of events to those that occurred between January 1, 1978, and December 31, 2002. A variety of parameters were examined, including: weather (i.e., METAR, also known as “aviation routine weather reports”), aircraft characteristics from Type Certificate Data Sheets or the FAA’s Aircraft Registry, level of pilot experience, and operating rules (e.g., FAR Parts 91 and 135).

Some notable observations from this data analysis are:

- Freezing rain was involved in 33 percent of the total events that involved precipitation,
- The ASRS reports indicated that although pilots attempt to minimize the amount of ice accretion by using rapid descent, their efforts are often hampered by Air Traffic Control requirements.

3.2 Petty/Floyd Review of U.S. Airframe-Icing Accidents

A review of U.S. airframe-icing accidents was conducted by the NTSB (ref. 3) and the overall objective was to update a study of aircraft icing hazards that focused on accidents that occurred in the 1970’s and the 1980’s (ref. 18). Petty and Floyd (ref. 3) used NTSB accident data from 1982 - 2000 and examined three types of aircraft operations: Part 91, Part 121, and Part 135. They also looked at the month, phase of flight, location (U.S. state) in which the icing accidents occurred, and the highest certification of the pilot in command at the time of the accident. The majority of airframe accidents occurred in Part 91 (80.6 percent), followed by Part 135 (17.6 percent), and Part 121 (1.7 percent). However, during the time period that was studied, 60 percent of Part 121 accidents were fatal compared with 47 percent of Part 91 and 26 percent of Part 135 airframe-icing accidents. Only 10 fatal Part 121 accidents occurred in the period of observation. The number of Part 91 accidents dropped from a high of 49 at the beginning of the review period to 17 accidents in the year 2000, which correlated with the overall decrease in Part 91 accidents.

Petty and Floyd (ref. 3) stated in their report that GA and Part 135 are more likely to encounter icing conditions because they “fly at lower altitudes and slower speeds than air transport aircraft,” but they did not provide data in their report to support this assumption. For this reason

the engine type was also examined in the IRAC Accident/Incident Study, and the results were presented and discussed in Section 2.

3.3 Army Aircraft Icing Report

The Army Safety Center searched its database of 54,081 Army aircraft accidents and incidents that occurred from fiscal year 1985 to 1999 for events that were coded as “aircraft icing” or “significant weather,” such as sleet or freezing rain (ref. 17). A total of 255 events resulted from this query; however, based on the narrative summaries only 172 of these accidents were truly icing related. The remaining non-genuine icing accidents were not removed from the total icing accident data set because icing could not be definitively ruled out as a factor in the accidents. Of the 255 icing events, 85 involved fixed-wing aircraft and the remaining two-thirds involved helicopters. If we base our assumptions purely on the data, we can conclude that icing is not a high-frequency safety problem for the Army because it accounts for only 0.5 percent of the total accidents during the study period. However, these relatively small numbers are still of concern due to the Army’s strict regulations in regard to aircraft and icing conditions:

*“...aircraft will not be flown into known or forecast severe icing conditions”
(Aviation Flight Regulations, AR 95).*

The regulation also states that, if a flight is to be made into known or forecast moderate icing conditions, the aircraft must be equipped with adequate deicing or anti-icing equipment.

To mitigate the risks of icing-related events, better in-flight icing detection and preflight deicing capabilities were recommended in the report.

3.4 NASDAC Review of NTSB Weather-Related Accidents

The National Safety Data Analysis Center (NASDAC) is the former name of the current ASIAs (Aviation Safety Information Analysis and Sharing) system. The purpose of ASIAs is to enable the exchange of multiple types of aviation safety data and information. ASIAs staff members examined NTSB aviation accident and incident data from 1994 to 2003 to identify any events in which weather was a causal or contributing factor (ref. 18). The ASIAs staff also looked at the relationship between the types of weather that were involved in the events and other parameters, such as type of operation and phase of flight.

Weather was cited as a contributing or causal factor in 21.3 percent of the 19,562 accidents that occurred in the study period. Out of the 4,159 weather-related accidents, icing accounted for 7.0 percent of the total accidents. The significance of icing differs based on the operation type. For example, only 0.8 percent (i.e. one accident) of the 124 weather-related part 121 accidents involved icing, but icing was a factor in 10 percent and 7.1 percent of the Part 135 and Part 91 accidents, respectively.

3.5 Summary of Statistical Study Parameters

One of the reasons that a comparison of the results from various studies can be difficult is the differences in the study constraints and assumptions (see Table 11). Although many of these studies used the same accident and incident databases, often a subset of the database (e.g.,

specific event years, FAR operations) is used for analysis. For example, we examined the differences between the results of the ASIAs weather study (see section 3.4) and those from the NASA analysis of the recent NTSB accident and incident data (see section 2.1). The results of these studies differ for two primary reasons. First, the ASIAs study covers a subset (years 1994 – 2003) of the total accidents that were examined in the NASA study (years 1988 – 2003). In the NASA study data, six Part 121 icing-related accidents were identified (Two with loss of control in flight, two with loss of control during takeoff, one with loss of control during approach/landing and one with extensive engine damage). However, even if the data set is reduced to the same period as that used in the ASIAs study, three Part 121 accidents were identified in the NASA study, which still differs from the ASIAs results. The reason for this discrepancy is that the ASIAs analysis relied solely on NTSB accident-classification codes or primary accident cause to identify accident categories. Thus, according to the ASIAs analysis, the accident on October 31, 1994 in Roselawn, IN would be the only Part 121 event that is icing related. However, according to the NASA study, the Part 121 accidents that occurred on March 14, 1997 (ice ingestion in both engines), and March 19, 2001 (failure to maintain airspeed during an encounter with severe icing conditions), also are icing related.

Table 11. Summary of Statistical Study Parameters

Author/ study title	Operation type	Database(s)	Country of operations	Event years	Total number of icing events
Green	Part 91 Part 135	NTSB Accident, FAA AIDS, NASA ASRS	United States	1978 – 2002	645 (A/I) 299 (ASRS)
Petty/ Floyd	GA Part 135 Part 121	NTSB Accident	United States	1982 – 2000	583
Army Data Center	Part 91	Army Aircraft A/I	Worldwide (U.S. Army)	1985 – 1999	255
ASIAs	Part 91 Part 135S Part 135NS Part 121	NSTB Accident	United States	1994 – 2003	
NASA Analysis of NTSB Data	Part 91 Part 135S Part 135NS Part 121	NTSB Accident, FAA AIDS	United States	1988 – 2003	872 (NTSB) 520 (AIDS)
NASA Analysis of ASRS Data	Part 91 Part 121 Part 135	NASA ASRS	United States	1988 – 2007	663

4. REVIEW OF AVIATION SAFETY PRIORITY LISTS

In recent years, subject-matter experts have conducted a number of studies that included recommendations for improving the safety of the air transportation system. This section contains a review of these safety priority lists with special emphasis on the significance of icing in improving aviation safety.

4.1 Decadal Study of Civil Aeronautics

The Aeronautics Space and Engineering Board within the National Research Council used a modified quality function deployment (QFD) process to identify and rank research and technology challenges. This study (ref. 19) which was sponsored by NASA, began with a September 2005 kick-off meeting in Herndon, VA. A steering committee, along with several supporting panels, conducted a series of additional meetings, which culminated in a June 2006 report in which a total of 51 high-priority challenges were identified. Two of these high-priority challenges, A6 (Aerodynamics robust to atmospheric disturbances and adverse weather conditions, including icing) and D6 (Improved onboard weather systems and tools), are related to icing.

Challenge A6 is based on the need for additional research to develop techniques to monitor and mitigate adverse weather conditions, such as icing, wind shear, and free-stream turbulence. The expected results of this research include the development of three-dimensional icing-prediction tools and systems with better measurement and mitigation of upstream environmental conditions. In particular, better icing-prediction methods would help reduce the high cost of aircraft and helicopter icing certification. The recommendation was made that NASA conduct research in this area because the agency's icing wind tunnels and research aircraft would complement the infrastructure that is found in industry and academia. This challenge was also rated as being highly relevant to NASA's Mission.

Improved on-board weather systems and tools (challenge D6) are necessary to cost effectively integrate real-time weather information into four dimensional integrated control of flight. The goal is for aircraft to share on-board sensor data about wind, icing conditions, lightning, and turbulence via data links with ATC and other aircraft. This information would be used in the air traffic management (ATM) system to reduce delays, especially in high-traffic areas, and to prevent weather-related accidents. The rationale for NASA conducting research in this area was because the agency has "an outstanding research facility for icing tests and evaluation and the infrastructure to develop and test weather-related tools." The report also stated that this research is central to NASA's Safety and Capacity missions.

A third research and technology challenge that is related to icing, B13 (Improved propulsion system tolerance to weather, inlet distortion, wake ingestion, bird strike, and foreign-object damage) was also identified. One of the proposed outcomes of this challenge is the development of physics-based models that can more accurately predict the effects of adverse weather (e.g., rain, hail, ice) on fans, compressors, and combustor stability. Although this challenge received high scores as a national priority, it did not make the overall high-priority list because NASA has few facilities, such as icing tunnels, that are relevant to this challenge.

4.2 Review of NASA's Aerospace Technology Enterprise

The National Research Council was asked by NASA and the Office of Management and Budget (OMB) to review NASA's former Aerospace Technology Enterprise (currently known as the Aerospace Research Mission Directorate.) The review began in early 2003 and, at the time, the Aerospace Technology Enterprise comprised three programs: Vehicle Systems, Airspace Systems, and Aviation Safety. At the time of the review, the Aviation Safety Program contained an aircraft icing subproject, which the committee deemed "the best technical work in the Aviation Safety Program" and "a unique national asset that is vital to the air transportation community, both civil and military." In the final report, which was published in 2004, the committee recommended that NASA continue the research to understand and mitigate aircraft icing. Some specific future research areas that were identified in the report include additional investigations to determine the effects of icing on aircraft aerodynamics, the development of methods to sense and document actual icing conditions, and smart icing systems. The report also advocated increased research in the areas of anti-icing fluids and the assessment of holdover times.

4.3 CAST/JIMDAT Safety Implementation Plans

The Commercial Aviation Safety Team (CAST) was formally established on June 23, 1998. Its mission is to provide government and industry leadership to develop and focus implementation of an integrated, data-driven strategy to improve commercial aviation safety. The members of CAST are a variety of stakeholders, including representatives from government, industry, pilot groups, air traffic controllers, and others. The Joint Implementation Data Analysis Team (JIMDAT) was formed by CAST to develop methods for prioritizing safety-enhancement implementation plans. JIMDAT accomplishes this mandate by:

- Estimating the potential risk decrease.
- Tracking those projects that are selected for implementation.
- Evaluating project outcomes to determine whether the estimated risk was lessened.
- Assessing any improvements that are identified outside of CAST.
- Identifying other areas of interest beyond the six prioritized FAA Safer Skies Agenda accident categories.

In its original list of recommendations to CAST, JIMDAT proposed a Safety Enhancement (SE) to release the risk of loss of control caused by icing:

SE 39: Criteria for Flight in Icing Conditions for New Airplane Designs

To reduce fatal accidents due to loss of control, recommend and support the development of amended icing certification criteria, for new airplane designs not equipped with evaporative (i.e. hot wing) systems, that include performance and handling qualities requirements for the following:

- *Residual ice*
- *Intercycle ice*
- *Delayed anti-icing/deicing system activation*
- *Deicing/anti-icing system malfunction*

JIMDAT considers SE 39 to be an ongoing enhancement that has not been completed. Over the years, JIMDAT has made modifications to its original list of safety enhancements and has

identified additional SE's that are either appropriate for long-term research or address the "remaining risk" in the air transportation system. One of the research SE's is related to icing:

SE 119: Loss of Control – Icing (research)

For aircraft that incorporate non-evaporative ice protection systems, develop systems that sense the presence of ice accretion on the aircraft, automatically activate and manage the ice protection systems, and provide the pilot with feedback including the effect on measured aircraft performance, stability, and control.

- *Provides annunciation that alerts the crew to respond appropriately to the icing hazard.*
- *Ground- and aircraft-based means of detection of meteorological icing conditions.*
- *Define the effects of all ice accretions, with particular emphasis on the roll effect due to ice-contaminated wings.*
- *Understand the effects of super-cooled large droplets (SLD).*

The three icing-related "remaining risk" SE's that JIMDAT has recommended for approval by the CAST are as follows:

SE 133: Turboprop Aircraft Ice Detection Systems

For all turboprop aircraft with non-evaporative ice protection systems and non-powered flight controls used in Part 121 operations, manufacturers should: (1) For new type designs, adapt and implement systems that automatically detect ice, measure the rate of ice accretion, and provide annunciation to the flight crew and (2) For current turboprop production aircraft and existing type design, conduct a study to determine the feasibility of installing systems that automatically detect ice, measure the rate of ice accretion, and provide annunciation to the flight crew

SE 134R1: Aircraft Design – Avionics

Avionic equipment manufacturers and aircraft manufacturers should develop and install smart pitch guidance systems on new type designs to prevent over rotation in conjunction with a low energy state or aerodynamic degradation due to the presence of ice on critical flight surfaces. The smart pitch avionics system should provide to the flight crew appropriate flight guidance information, the current aircraft energy state and performance margins with respect to stall speed and maximum angle of attack for all icing conditions for which an aircraft has been certified.

SE 136: Training – Engine Surge Recovery

To prevent fatal accidents resulting from an engine surge caused by ice ingestions, airlines should provide adequate training for flight crews to ensure appropriate responses to this event. This training should include engine-out identification, engine surge recovery procedures, and associated aircraft recovery in all the varying combinations. Key to this training is that it be accomplished prior to the pilot being assigned to the line or introduced to new equipment.

To understand the relative significance of these icing enhancements, Figure 20 contains the potential impact of all of the recommended enhancements on reducing risk. Note that only 6 out of the 19 total enhancements have higher risk-reduction scores than the 3 icing enhancements. Four of the higher scoring enhancements are related to cargo and the other two are related to maintenance/systems.

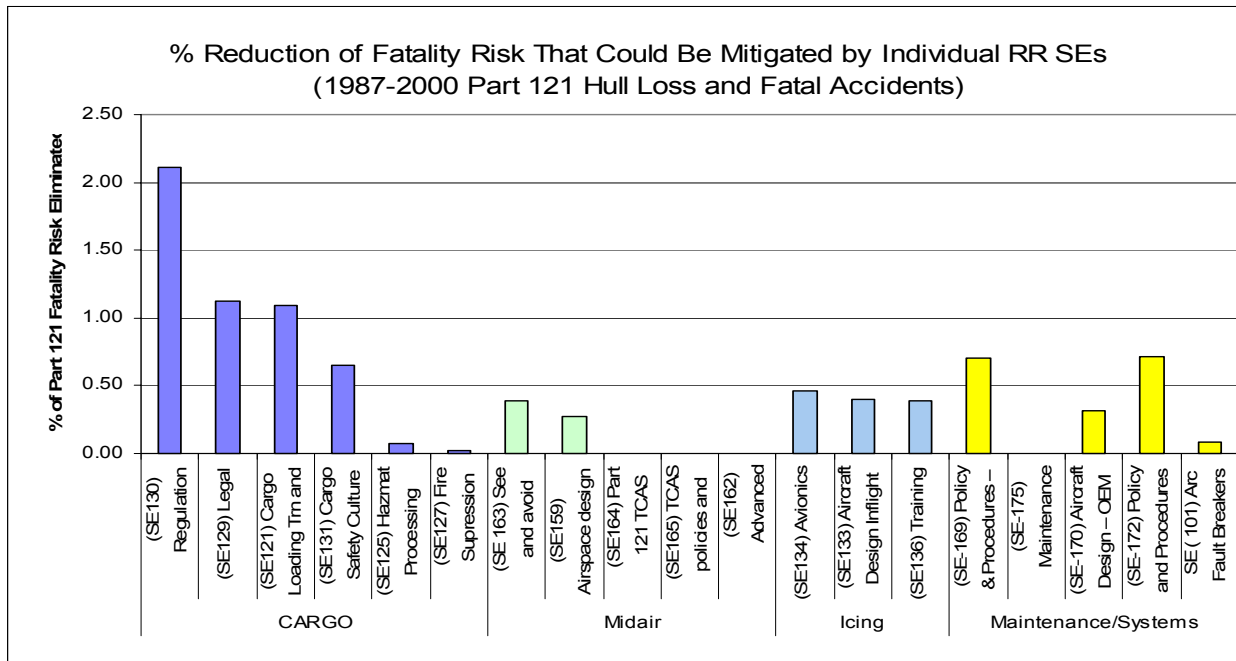


Figure 20. JIMDAT “remaining risk” safety enhancements.
(Source: Rob Noges, JIDMAT member)

Two additional icing-related enhancements have been examined by JIMDAT but have not been submitted for CAST approval. One of the factors for delaying their recommendation is the expected cost of implementing these SE's as compared with their impact on risk reduction. The impact of these additional enhancements on the risk to the air transportation system has not been calculated. The two additional enhancements are:

SE 135: Ground Operations

To prevent fatal accidents resulting from ice-contaminated wings, control surfaces, and other critical surfaces, aircraft operators, airport authorities, regulators, and air traffic control should develop and implement ground operations policies and procedures to reduce the likelihood of ice contamination on flight critical surfaces.

SE137: Weather Information

To prevent fatal accidents and incidents resulting from inadequate aircraft deicing and anti-icing and runway and taxiway snow removal operations due to insufficient information on surface weather conditions, weather information providers should provide airport-zone-specific advanced- detection and forecast

products (e.g., Weather Support to Deicing Decision Making (WSDDM)) to operators, flight crews, and airport authorities for ground operations.

Aircraft Icing Research Alliance (AIRA)

The Aircraft Icing Research Alliance is an organization that was formed in 2002 to increase coordination of aircraft icing research. Members of the AIRA include representatives from NASA, the FAA, the National Oceanic and Atmospheric Administration (NOAA), Transport Canada (TC), Environment Canada (EC), the National Research Council of Canada (NRC), National Defense of Canada, and Defense Science and Technology Laboratory (DSTL) of the United Kingdom. Industry, academia, and other nations also participate in the AIRA either by assisting with setting research priorities or via joint research as part of an AIRA subcommittee.

The AIRA created a list of 87 icing-related research focus areas (RFA's), which are divided into six themes: (1) in-flight icing, (2) aircraft icing while on the ground, (3) runway winter contamination, (4) operations, human factors, and training, (5) safety and economic analysis, and (6) emerging technologies. The AIRA identified 17 of these as priority RFA's, and results are shown in Table 12. Note that three of the themes do not contain priority RFA's and the in-flight icing theme is further divided into seven sub-themes. (ref. 20)

Table 12. AIRA Priority Research Focus Areas (RFA's)

In-flight icing	Aircraft icing while on the ground	Operations, human factors and training
<p>Aerodynamic performance and handling qualities</p> <ul style="list-style-type: none"> ▪ Aerodynamic performance and handling qualities in icing <p>Atmospheric characterization</p> <ul style="list-style-type: none"> ▪ High ice-water content <p>Weather and forecasting</p> <ul style="list-style-type: none"> ▪ Nowcasting development and validation ▪ Dissemination of weather information ▪ Forecasting development and validation ▪ Remote sensing systems for icing detection <p>Facilities, simulators and instrumentation systems</p> <ul style="list-style-type: none"> ▪ Comparison of tools, techniques and facilities and the establishment of standards <p>Fundamental ice physics</p> <ul style="list-style-type: none"> ▪ Ice formation mechanics ▪ Scaling <p>Ice shedding</p> <ul style="list-style-type: none"> ▪ Ice shedding mechanisms <p>Propulsion and Power Plant Icing</p> <ul style="list-style-type: none"> ▪ High ice-water ingestion 	<ul style="list-style-type: none"> ▪ Fluid integrity detection system ▪ Performance effects of limited contamination 	<ul style="list-style-type: none"> ▪ Flight crew training module for operations in icing conditions

4.5 NTSB Most-Wanted List

The NTSB publishes an annual list (ref. 21) of the most-wanted transportation safety improvements for various modes of transportation (e.g., highway). In 1996, a recommendation was added to the aviation list to “reduce dangers to aircraft flying in icing conditions.” The Board’s specific recommendation to the FAA about this issue is as follows:

Use current research on freezing rain and large water droplets to revise the way aircraft are designed and approved for flight in icing conditions.

Conduct additional research with NASA to identify realistic ice accumulations and incorporate new information into aircraft certification and pilot training requirements.

NTSB icing expert Dan Bower stated in 2005 (ref. 22)

“...the industry may not yet fully appreciate the danger of even a small amount of ice on upper wing surfaces...Research results have shown that fine particles of frost or ice, the size of a grain of table salt and distributed as sparsely as one per square centimeter over an airplane’s wing’s upper surface can destroy enough lift to prevent that airplane from taking off.”

The FAA responded to this recommendation by making revisions to and developing new rules to address icing, which resulted in a total of five rule-making activities. Beyond these activities, the FAA contends that additional actions are not necessary in regard to flight in icing conditions. The NTSB recommends additional actions and although the number of icing-related accidents and serious incidents is small, considers icing to be a significant aviation danger. In June 2007, the NTSB asked the FAA to complete the following actions: (1) complete efforts to revise icing certification criteria, testing requirements, and restrictions on operations in icing conditions and (2) evaluate all aircraft that are certified for flight in icing conditions using the new criteria and standards. (ref. 23)

4.6 Summary of Icing Research Priorities

Based on the prioritized lists that were discussed earlier and on additional information in regard to icing-related atmospheric problems (ref. 24-26), the following are the highest priorities for aviation icing-related research:

- **Improved propulsion system tolerance to weather**
 - Develop more accurate physics-based models that can predict the effects of adverse weather on fans, compressors, and combustor stability.
 - Conduct research on high ice-water ingestion.
 - Conduct research on high-altitude ice-particle ingestion.
- **Development of methods to sense and document actual icing conditions**
 - Develop systems with better measurement and mitigation of upstream environmental conditions.
 - Develop improved on-board weather systems and tools (including incorporation of on-board sensor data about wind, icing conditions, etc.)
 - Develop and validate better methods for nowcasting.

- Develop and validate better methods for forecasting.
- Develop dissemination of weather information.
- Develop remote sensing systems for icing detection.
- **Research to identify realistic ice accumulations to improve aircraft certification and pilot training**
 - Conduct research on freezing rain and large water droplets to revise the manner in which aircraft are designed and approved for flight in icing conditions.
 - Develop flight crew training module for operations in icing conditions.
 - Conduct research on ice formation mechanics.
 - Measure performance effects of limited contamination.
 - Assess holdover times.
- **Aircraft performance and handling qualities in icing**
 - Research the effects of icing on aircraft aerodynamics.
 - Study ice shedding mechanisms.
 - Research anti-icing fluids.
 - Define the effects of ice accretions, especially the effect on roll characteristics.
 - Develop smart pitch guidance systems.
 - Develop smart icing systems.

5. FUTURE ICING RESEARCH REQUIREMENTS

The expected outcome of this analysis is to provide input for future icing research requirements, including the appropriate alignment within the AvSafe Program. Specifically, these requirements should address whether future icing research should be conducted through the IRAC project or through another AvSafe project, such as the Integrated Vehicle Health Management (IVHM) Project or the Integrated Intelligent Flight Deck (IIFD) Project. The rationale is that although most of the icing research priorities are in the area of flight control, others are related to sensing and identification, which are interests for the IIFD and IVHM projects, respectively. This section summarizes the published goals and objectives for the IRAC, IVHM, and IIFD projects, examines their relevance to the icing research priorities that have been presented in the previous section, and presents suggestions for future NASA icing research.

5.1 IRAC Goals and Objectives

The objectives of the NASA Aviation Safety Program (AvSafe) (ref. 2) are:

- *“Conduct long-term, cutting-edge research that will produce tools, methods, and technologies to improve the intrinsic safety attributes of current and future aircraft.”*
- *“Overcome safety technology barriers that would otherwise constrain full realization of the Next Generation Air Transportation System.”*

According to the IRAC Technical Plan (ref. 1), the IRAC project will conduct research to advance the state of aircraft flight control to provide onboard control resilience for ensuring safe flight in the presence of adverse conditions. The goal of the IRAC project is to arrive at a set of validated multidisciplinary integrated aircraft control design tools and techniques for enabling safe flight in the presence of adverse conditions (e.g. faults, damage, upsets). The objective is to advance the state of the art of adaptive controls as a design option to provide enhanced stability and maneuverability margins for safe landing. Adverse events include loss of control that is caused by environmental factors and actuator and sensor faults or failures and will expand to include more complicated damage conditions.

The IRAC project goals and objectives (refs. 1 and 27) are graphically depicted using an objectives tree format (ref. 28) in Figures 21 and 22.

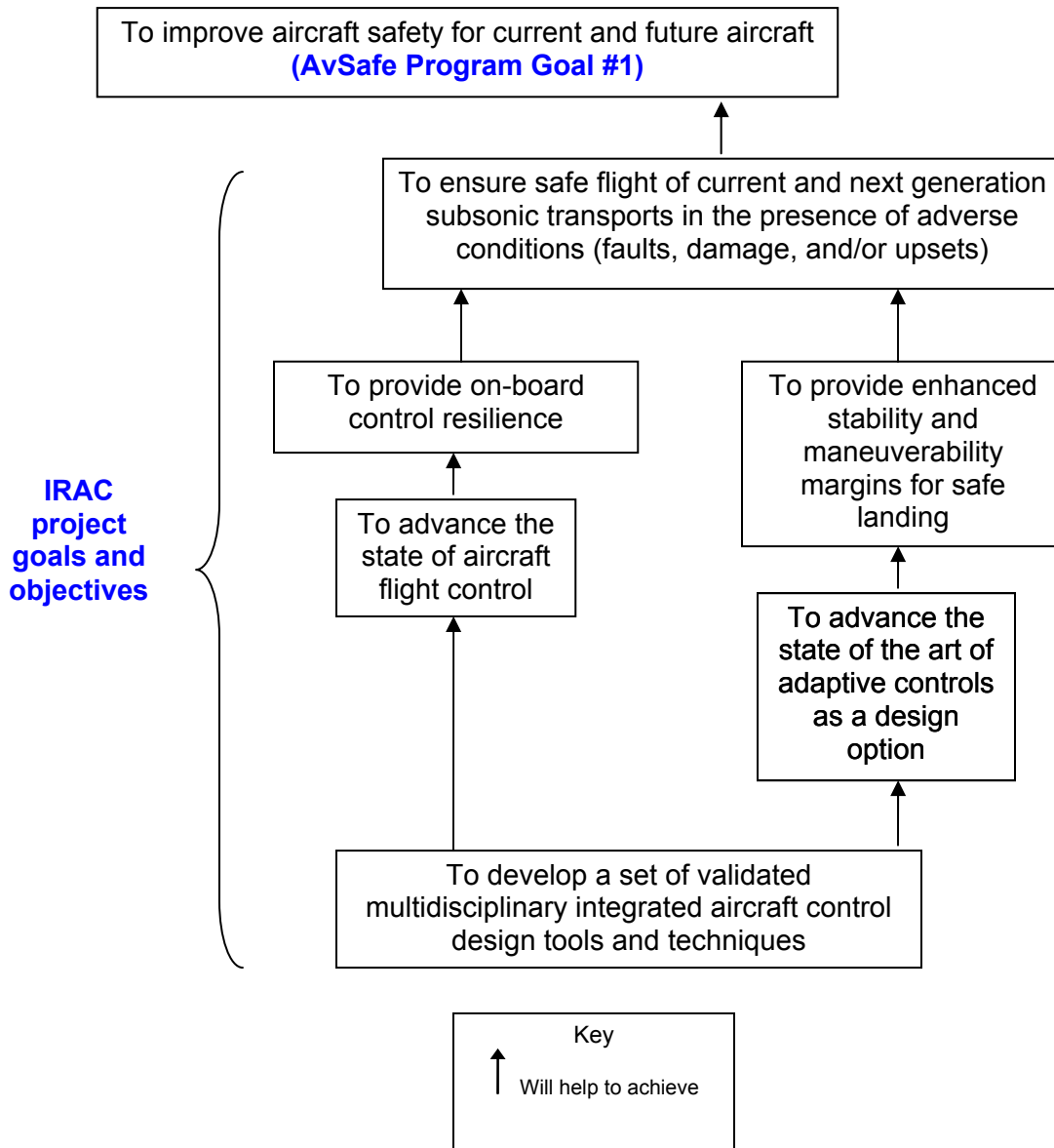


Figure 21. NASA IRAC objectives tree.

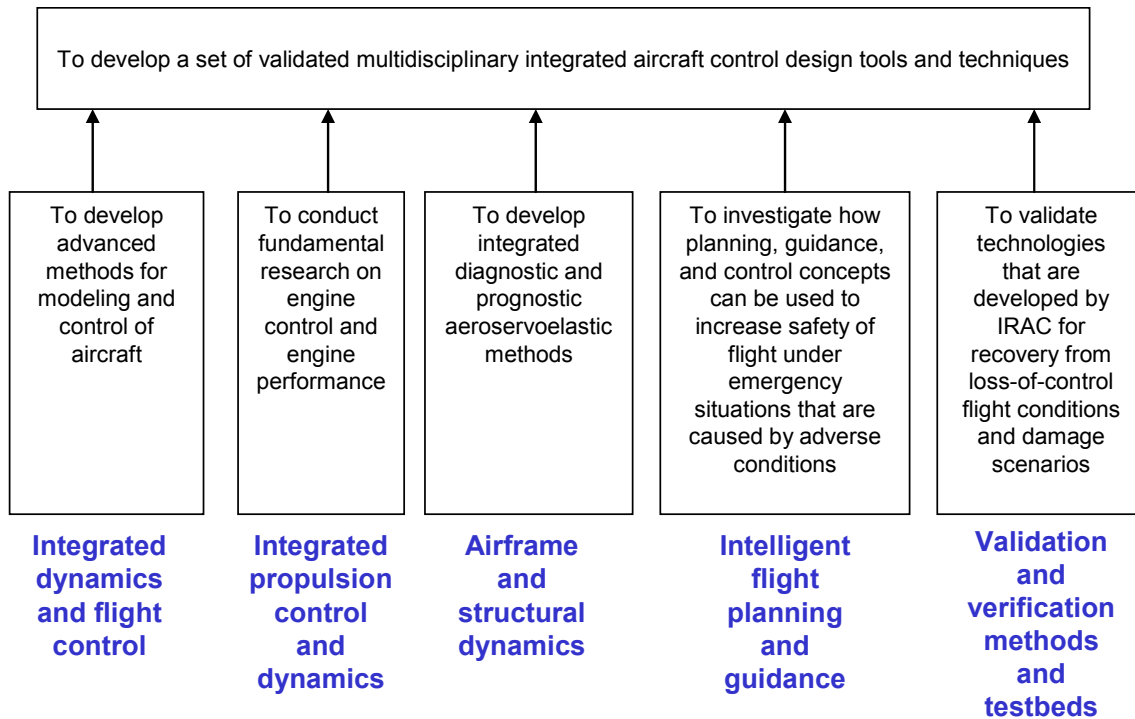


Figure 22. NASA IRAC subproject objectives tree.

5.2 IVHM Goals and Objectives

The goals of the IVHM project are to: (1) reduce system and component failures as causal and contributing factors in aircraft accidents and incidents and (2) provide continuous on-board situational awareness of the state of vehicle health for use by the flight crew, ground crew, and maintenance depot. The purpose of this research is to develop technologies that will enable the early detection of system/component degradation and damage and thereby provide the ability to prevent or gracefully recover from in-flight failures. The objectives of the IVHM project are as follows (ref. 29):

- *Develop tools and techniques to:*
 - *Determine the state of subsystems such that the state of the entire vehicle can be determined for accurate prognosis.*
 - *Diagnose coupled degradation/malfunction/failure/hazard conditions and predict their effects on vehicle safety.*
 - *Mitigate damage/degradation/failures inflight.*
- *Develop a public database and testing capabilities for IVHM technologies.*

5.3 IIFD Goals and Objectives

The IIFD project within the AvSafe Program conducts research that is shared with government and industry to create future flight decks that are safer and more capable. One of the advanced features that is envisioned for these future flight decks is the integration of external hazard

sensors with decision-aiding functions. The objectives tree for the IIFD project is shown in Figure 23 (ref. 30).

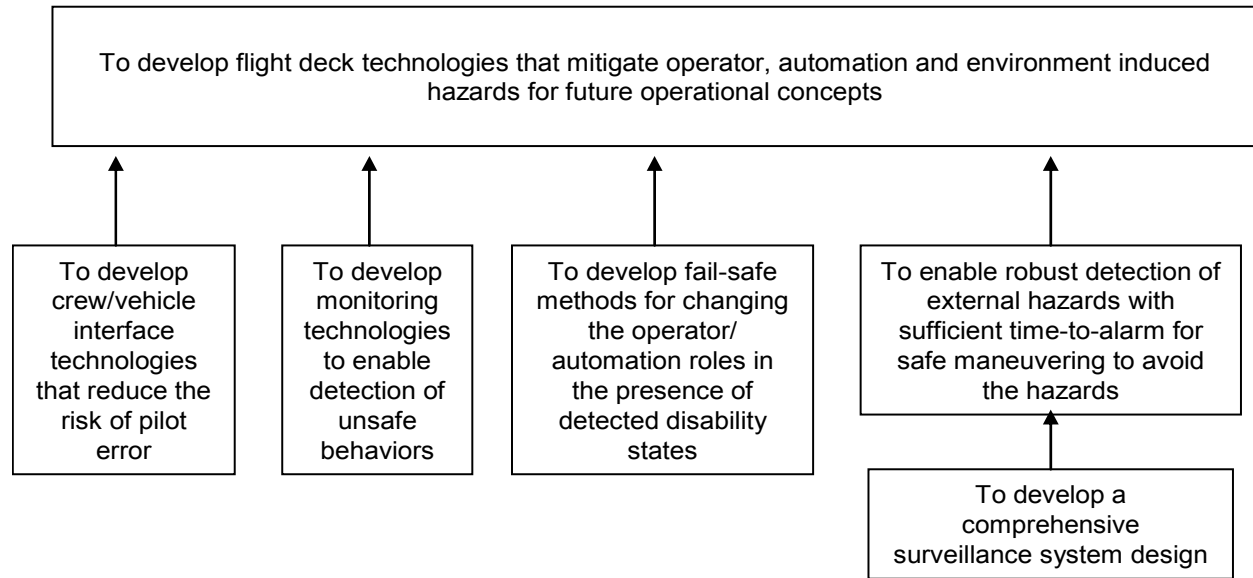


Figure 23. NASA IIFD project objectives tree.

5.4 Mapping of Goals to Icing Research Priorities

High-priority icing research issues were summarized in section 4. Based on the current stated goals and objectives of the AvSafe IRAC, IIFD, and IVHM projects, Table 13 provides the suggested mapping of these goals to the icing research issues. Note that certain research issues do not map to an AvSafe project; this is a result of the strict alignment to the current project objectives and should not be interpreted as a lack of technical expertise within NASA in these icing research areas.

Table 13. NASA AvSafe Project Goals Mapped to Icing Research Priorities

Icing Research Priorities	Aviation safety program		
	IRAC Flight control	IVHM On-board sensing	IIFD Remote sensing
Improved propulsion system tolerance to weather			
Development of more accurate physics based models that can predict the effects of adverse weather on fans, compressors and combustor stability	X		
High ice water ingestion	X		
High altitude ice particle ingestion	X		
Development of methods to sense and document actual icing conditions			
Systems with better measurement and mitigation of upstream environmental conditions			
Improved onboard weather systems and tools (including incorporation of onboard sensor data about wind, icing conditions, etc.)		X	X
Nowcasting development and validation			
Forecasting development and validation			
Dissemination of weather information			X
Remote sensing systems for icing detection			X
Research to identify realistic ice accumulations to improve aircraft certification and pilot training			
Research on freezing rain (ZR) and large water droplets to revise the way aircraft are designed and approved for flight in icing conditions	X		
Flight crew training module for operations in icing conditions			
Ice formation mechanics	X		
Performance effects of limited contamination	X		
Assessment of holdover times			
Aircraft performance and handling qualities in icing			
Research on the effects of icing on aircraft aerodynamics	X		
Ice shedding mechanisms			
Anti-icing fluids			
Define the effects of ice accretions, especially the effect on roll	X		
Smart pitch guidance systems	X		
Smart icing systems	X	X	X

6. DISCUSSION AND CONCLUSIONS

Although FAR Part 135 operations have the highest percentage of icing-related events and no fatal Part 121 accidents have occurred since 1994, icing is still a safety concern across all categories of subsonic aircraft. As previously stated, when ramp- and security-related accidents are eliminated from the NTSB data set, 9.5 percent of the total fatal Part 121 accidents were attributable to icing, which is more than for Part 91 (3.7 percent), Part 135 Scheduled (8.3 percent) and Part 135 Nonscheduled (8.0 percent). Three of the six icing accidents in the NASA NTSB data study (see section 2.1) involved turboprop engines, while the remaining three accidents involved turbofan or turbojet engines. Aircraft with turboprop and reciprocating engines still comprise a significant portion of Part 121 operations. In 2004, 41 percent of the aircraft used by regional airlines had turboprop or reciprocating engines. Of the 663 icing incidents reported in the voluntary ASRS database for which an engine type was provided, 223 had reciprocating engines, but 208 had turbojet engines, and 87 had turboprop engines. Further, 141 of the 663 total icing-related incidents resulted in the crew declaring an emergency. In the Petty and Floyd review (ref.3) of airframe-icing accidents from 1982 to 2000, 60 percent of accidents for Part 121 were fatal compared with 47 percent for GA and 26 percent for Part 135 during the same time period. According to the Green Study (ref. 8), ASRS reports indicate that pilots try to minimize the amount of ice accretion by using rapid descent but their efforts are often hampered by ATC requirements. Even in military operations, icing still appears to be a problem. Only 0.5 percent of U.S. Army aircraft accidents are icing related, but this number is still of concern due to the Army's strict regulations that forbid flight into known or severe icing conditions.

A review of studies by subject-matter experts from the NRC, the CAST/JIMDAT, the AIRA, and the NTSB was summarized into four high-priority icing research areas: (1) improved propulsion system tolerance to weather, (2) development of methods to sense and document actual icing conditions, (3) research to identify realistic ice accumulations to improve aircraft certification and pilot training, and (4) aircraft performance and handling qualities in icing.

Based on the current stated goals and objectives of the AvSafe IRAC, IIFD, and IVHM projects, the suggested mappings of these goals to the icing research issues were listed in Table 13. As shown in Table 13, the IRAC project is encouraged to conduct work in all of the identified areas except for the "development of methods to sense and document actual icing conditions."

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14. ABSTRACT NASA's Integrated Resilient Aircraft Control (IRAC) Project is one of four projects within the agency's Aviation Safety Program (AvSafe) in the Aeronautics Research Mission Directorate (ARMD). The IRAC Project, which was redesigned in the first half of 2007, conducts research to advance the state of the art in aircraft control design tools and techniques. A "Key Decision Point" was established for fiscal year 2007 with the following expected outcomes: document the most currently available statistical/prognostic data associated with icing for subsonic transport, summarize reports by subject matter experts in icing research on current knowledge of icing effects on control parameters and establish future requirements for icing research for subsonic transports including the appropriate alignment. This study contains: (1) statistical analyses of accident and incident data conducted by NASA researchers for this "Key Decision Point", (2) an examination of icing in other recent statistically based studies, (3) a summary of aviation safety priority lists that have been developed by various subject-matter experts, including the significance of aircraft icing research in these lists and (4) suggested future requirements for NASA icing research. The review of several studies by subject-matter experts was summarized into four high-priority icing research areas. Based on the Integrated Resilient Aircraft Control (IRAC) Project goals and objectives, the IRAC project was encouraged to conduct work in all of the high-priority icing research areas that were identified, with the exception of the developing of methods to sense and document actual icing conditions.						
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